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Can illumination estimates provide the basis for color constancy?

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Objects hardly appear to change color when the spectral distribution of the illumination changes: a phenomenon known as color constancy. Color constancy could either be achieved by relying on properties that are insensitive to changes in the illumination (such as spatial color contrast) or by compensating for the estimated chromaticity of the illuminant. We examined whether subjects can judge the illuminant's color well enough to account for their own color constancy. We found that subjects were very poor at judging the color of a lamp from the light reflected by the scene it illuminated. They were much better at judging the color of a surface within the scene. We conclude that color constancy must be achieved by relying on relationships that are insensitive to the illumination rather than by explicitly judging the color of the illumination.

Keywords: color vision, surface properties, matching, color constancy, chromaticity

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Introduction

The light reflected from an object to the eye depends both on the reflectance of the object's surface and on the illumination. The interplay between surface reflectance and illumination produces ambiguity in the retinal image; many combinations of reflectance and illumination give rise to the same light on the retina. One is frequently only interested in the surface reflectance, so the visual system attempts to discount the contribution of the illumination to produce a stable perceptual representation of the object's surface reflectance. This ability is known as color constancy.

The hypothesis that states that the visual system estimates the illumination of a scene and uses this estimate to determine the reflectance of surfaces of interest is known as the "Illuminant Estimation Hypothesis" (Beck, 1972; Epstein, 1973; Koffka, 1935). Many computational theories of color constancy (e.g., Brainard & Freeman, 1997; Buchsbaum, 1980; D'Zmura & Lennie, 1986) are based on this hypothesis. An obvious strategy for estimating the illuminant's color is by analyzing the light from the illuminant itself. However, the illuminant is often not directly visible, or too bright to estimate directly, so one will often have to rely on less direct sources of information. Assumptions about the way in which the visual system infers the color of the illumination include the assumption that the average reflectance of the whole scene is gray (Buchsbaum, 1980; but see Granzier, Smeets, & Brenner, 2006) or that the brightest surface is white (Land & McCann, 1971). The correlation between color and luminance within the scene may also help to estimate the illuminant (Golz & MacLeod, 2002; but see Granzier, Brenner, Cornelissen, & Smeets, 2005). Obviously, these assumptions are not always correct, but there need not be a single principle for estimating the illumination. Relying on a combination of assumptions could provide a robust judgment of the illuminant.

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Knowing the color of the illumination may be of interest to the visual system, for instance for estimating the time of day or predicting the weather (Jameson & Hurvich, 1989; Lotto & Chittka, 2005; Zaidi, 1998). We are able to differentiate morning light from noon light and tungsten light from fluorescent light, even if the illuminants themselves are invisible. The fact that people are aware of the illumination is evidence against the hypothesis that all information regarding the illuminant is automatically discarded early in visual processing.

The Illuminant Estimation Hypothesis predicts that if subjects are good at estimating the illuminant's color, they will also be good at estimating surfaces' colors (i.e., they will exhibit high amounts of color constancy). If subjects are poor at estimating the illuminant's color, they will be poor at estimating surfaces' colors. Systematically incorrect estimates of the illuminant will result in systematic patterns of errors in subjects' surface color estimates. Brainard and colleagues (Brainard, Brunt, & Speigle, 1997; Speigle & Brainard, 1996) have shown that the patterns of errors in surface color estimation are consistent with incorrectly estimating the scene illumination and then discounting the illuminant using this incorrect estimate (i.e., they can be described by an "equivalent illuminant"). However, one could also obtain color constancy without estimating the illumination; by relying on illuminant-independent strategies (e.g., Land, 1977). Such mechanisms need not be perfect. Perceiving the illuminant's color could be a (useful) manifestation of an imperfection in color constancy. Judging the degree of ripeness of fruit in a tree does not really require very exact information about surface reflectance, so small errors could be tolerated.

Given the fact that the Illuminant Estimation Hypothesis has been around for so long, it is surprising to see how few attempts have been made to test it. Several studies (Khang & Zaidi, 2004; Linnell & Foster, 2002) claimed to investigate illuminant color perception, but they compared similar scenes under different illuminants, rather than having people report about the illuminant itself. The Illuminant Estimation Hypothesis has been studied more extensively in the lightness domain (e.g., Gilchrist & Jacobsen, 1984; Logvinenko & Menshikova, 1994; Rutherford, 2000; Rutherford & Brainard, 2002).

If estimating the illuminant is essential for obtaining color constancy, we should find a clear relationship between how well people can judge the illuminant's color and the level of color constancy. If the Illuminant Estimation Hypothesis is incorrect, and the visual system uses illuminant-independent strategies to achieve color constancy, there need not be a relationship between color constancy and judgments of the illuminant's color. We therefore set out to test how well subjects can estimate the illuminant's color and whether their color constancy is consistent with this estimate.

General methods

Subjects

Seven subjects took part in the two experiments. They had normal color vision as tested with Ishihara color plates (Ishihara, 1969). One subject was an author (J.S.). The other subjects were naïve as to the purpose of the experiment. The experiments were carried out at the department of neuroscience in Rotterdam as part of a research program that was approved by the local ethics committee.

The lamps

The lamps were presented one at a time in random order. The luminance (as measured with a Minolta CS-100A chroma meter) was set so that the light reflected from a white piece of paper at the center of the experimental scene was 24 cd/m^2 for all lamps. This was achieved by manipulating the voltage of the input to the lamps.

Four different lamps were used to illuminate the scene (Philips spotline series). The 1931 CIE$_{xy}$ coordinates of the light from these lamps were (0.315, 0.565), (0.461, 0.412), (0.505, 0.448), and (0.513, 0.414). The subjects could not see the lamps and did not know how many lamps there were, or their colors. The lamps had fixed positions. Two lamps were to the left of the scene and two lamps were to the right of the scene. The scene was never illuminated by more than one of the four lamps.

Figure 1. The same scene illuminated by two different lamps.

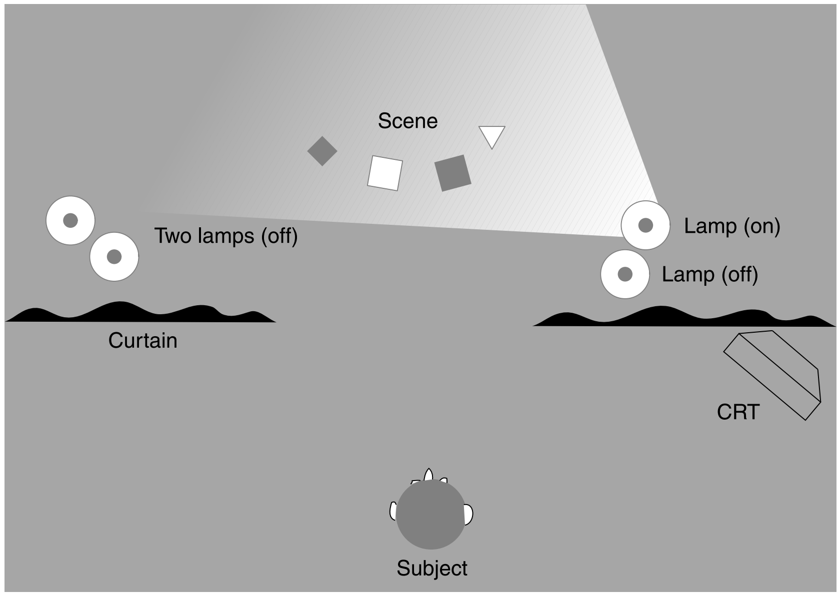

Figure 2. Schematic overview of the set-up for illuminant estimation. Subjects adjusted the color of a disk on the CRT to match the color of the light from each of the four lamps. A curtain separated the scene from the monitor.

The scenes

We used real 3-dimensional scenes and real illuminants to create optimal circumstances for estimating the illuminant's color (see Figure 1). We included smoothly curved and shiny objects of various colors (providing clear highlights; Lee, 1986) and the objects were placed in a manner that gave rise to shadows and mutual illuminations (Bloj, Kersten, & Hurlbert, 1999; Drew & Funt, 1990). The scene was in front of the subjects, at a distance of 100–250 cm and was seen through an opening in a black curtain (see Figure 2). There was a CRT monitor to the right of the scene, in front of the curtain, 100 cm from the subject. The walls of the room were black.

We are quite good at remembering objects' colors (Bertulienė & Bertulis, 1991; Sachtler & Zaidi, 1992). Helmholtz (1867/1962) and Hering (1874/1964) proposed that memory of the colors of objects could help achieve color constancy, and object familiarity has indeed been found to improve color constancy (Hansen, Olkkonen, Walter, & Gegenfurtner, 2006; Hurlbert & Ling, 2004; Jin & Shevell, 1996; Ling & Hurlbert, 2006), although the effects are quite small. In order to determine whether the presence of objects of which the reflectance is known helps in estimating the illuminant's color we used two scenes; one with objects of which the colors are known (objects with object specific or brand specific colors; Figure 3A) and one with objects that have an unknown color (objects that can be bought in many colors; Figure 3B).

Illuminant estimation

In order to determine how well subjects could judge the color of the illumination, subjects were asked to set the color of the light from a disk at the center of a calibrated

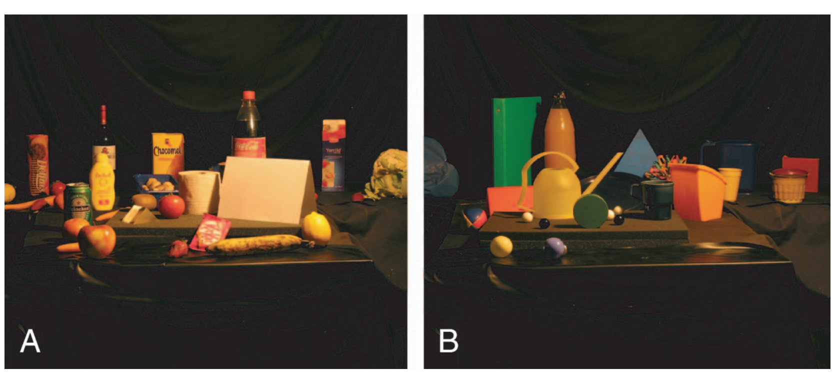

Figure 3. Scenes with objects with known (A) and unknown (B) colors.

Sony GDM-FW 900 Trinitron monitor (48 cm × 31 cm; 1920 × 1200 pixels; 90 Hz; 8 bits per gun) to match their estimate of the color of the light from the lamp illuminating the scene. The disk on the monitor had a diameter of 3.5 cm (about 5 deg). Its luminance was 10 cd/m^2. The rest of the screen was dark. We used a single surface on a screen to ensure that there could be no confusion about this being emitted light.

Procedure

Subjects could vary the color of the adjustable disk within a two dimensional CIE isoluminant color space by moving the computer mouse. They indicated that they were content with the match by pressing a button. Once they did so, the lamp was switched off and shortly afterwards a new lamp was switched on. The initial color of the adjustable disk was chosen at random from within the range that could be rendered with our equipment. After adapting for 5 minutes to the relatively low room illumination with one of the lamps, each subject made matches for 40 minutes. Depending on how fast they were, this gave 8–17 matches per lamp. The lamps were presented in random order. Subjects performed the estimation task twice, in two sessions; one with "objects with known colors" and one with "objects with unknown colors." The order of the sessions was counterbalanced across subjects.

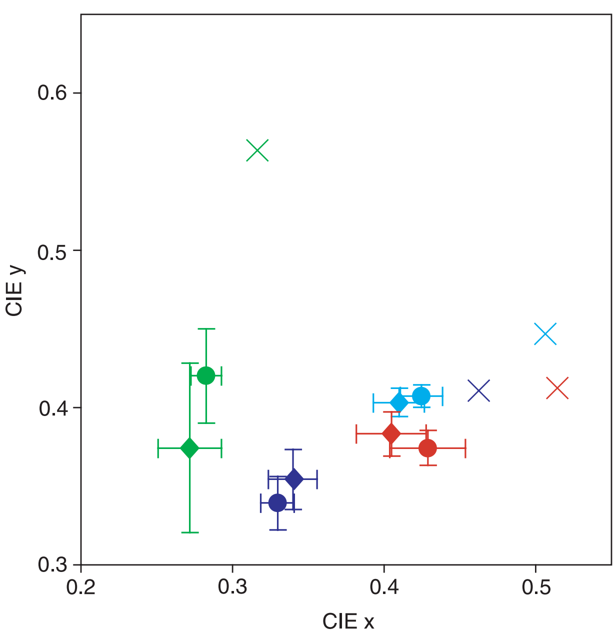

Figure 4. Estimates of the color of the lamps in the presence of objects with known colors (disks) or with unknown colors (diamonds). Each symbol shows the mean of the subjects' average matches for one lamp (indicated by the different colors). The correct values are indicated by the crosses.

Results and discussion

We determined the mean CIE$_{xy}$ coordinates of each subject's matches for each of the four lamps. Figure 4 shows the average coordinates for each lamp with their standard errors (across subjects). The coordinates of the light from each of the lamps are also shown. Inspection of Figure 4 shows that the matches were clearly different for the different lamps, but subjects consistently underestimated the saturation of the light from the lamps (we believe this to be a good description although the data can also be described as a shift towards blue light). There was considerable variability within individual subjects' estimates for each lamp: average standard deviations of 0.078 and 0.064 for the x and y coordinates, respectively. Illuminant color estimation was not much better in the scene with objects that have a known color than it was for the scene in which the objects do not have a known color (compare disks with diamonds).

Color constancy

Our next step was to see whether surface reflectance is judged just as poorly as the illuminant. Since we did not find any real difference between the two scenes, we only used the scene with "known colors" for our color constancy experiment.

Procedure

Subjects selected the sample of a pantone professional color selector (Pantone Inc., New Jersey, USA) that best matched the surface of one of three wooden test plates (the number of plates was unknown to the subjects and only one was visible at a time; see Figures 5 and 6). We used the same four lamps that were used in the "illuminant estimation" part of the experiment. The scene was illuminated by one of these four lamps at a time. The samples of the color selector were illuminated by the reference lamp, which was very similar to one of the lamps: (0.452, 0.411). Subjects were instructed to indicate the color in which the wooden test plate had been painted.

The test plates

The CIE$_{xy}$ color coordinates of the light reflected by the three wooden test plates under the reference lamp (the one illuminating the color selector) are (0.308, 0.354), (0.444, 0.470), and (0.387, 0.516). Thus, for perfect color constancy, subjects should select the sample that reflects light with these coordinates. The painted wooden plate was placed in the middle of the scene, always at the same

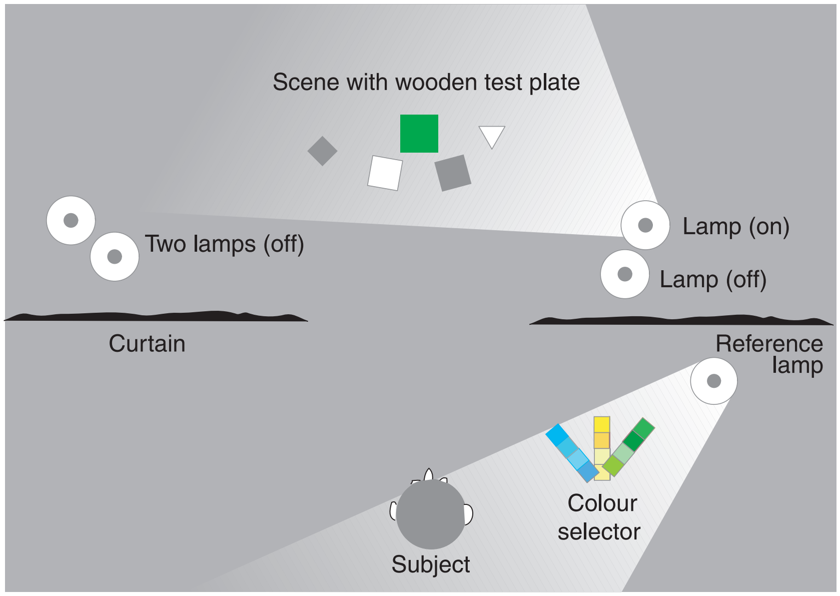

Figure 5. Schematic overview of the set-up for reflectance estimation. Subjects selected the sample from the color selector that best matched the wooden test plate. The color selector was illuminated by a reference lamp. The scene with the wooden test plate was illuminated by the same lamps that were used when estimating the color of the illumination.

location and with the same orientation with respect to the observer.

The three wooden test plates were each illuminated by each of the four lamps of the illuminant estimation experiment, giving a total of 12 combinations of surface and illumination. Each combination was presented three times, in random order, leading to a total of 36 matches for each subject. This color constancy experiment took about 90 minutes (per subject).

Analysis

The first step was to measure the color coordinates of each of the chosen selector samples when illuminated by

Figure 6. The scene with one of the three test plates as seen from the subjects' vantage point.

the reference lamp. We will call these values subjects' "actual matches." We determined the mean coordinates of each subject's matches for each of the twelve experimental conditions. We then averaged these coordinates across subjects and calculated the associated standard errors. A total absence of color constancy would mean that subjects match the color of the light that reaches their eyes. We will refer to such a match as a "match of reflected light." A perfect match of surface reflectance is only possible if the test plates' surface reflectance is identical to that of one of the selector samples. Otherwise surfaces that yield a perfect spectral match under one illumination will not do so under a different illumination, so there is no perfect match. We chose to consider a sample that has the same CIE_{xy} coordinates as the test plate under the lamp illuminating the color selector as a "correct match." This value was determined by measuring the light reflected by the test plate under the lamp that illuminated the pantone selector during the experiment.

If the Illuminant Estimation Hypothesis is correct, we should find a correlation between how good subjects are at estimating the illuminant and how accurately they match the reflectance of the wooden test plates. We therefore determined the deviations of subjects' illuminant matches from the correct matches (distances in CIE_{xy}) and the average deviations of subjects' matches for the wooden test plates from the correct matches (distances in CIE_{xy}) and calculated correlation coefficients between both deviations (across subjects for each lamp).

Finally, we determined how we would expect subjects to match the surfaces considering how they misjudged the illumination in the first part of the study. For details on how this was done, see Appendix A. In short, we assumed that the color of the direct light from the monitor, as matched in the first part of this study, directly represents the color of the illumination that subjects use to estimate the wooden test plate's reflectance from the light that it reflects. We also assume that surfaces reflect a certain percentage of the light that stimulates each kind of cone, irrespective of the illumination (the validity of this assumption will be discussed when presenting the results). Considering how poorly subjects judged the colors of the lamps illuminating the scene, it is reasonable to expect them to also misjudge the color of the lamp illuminating the pantone color selector. We therefore determined the CIE_{xy} coordinates of the light from the reference lamp that would best account for the matches (minimizing the summed square distance in CIE_{xy} color space between the predictions and the actual matches). The hypothetical chromaticity of the reference lamp was the same for all conditions but differed between subjects. We will refer to the values based on the misjudged illumination of the scene and the fit chromaticity of the reference lamp as the "best possible match based on estimating colors of lamps." Performing this fit is comparable with finding the most likely "equivalent illuminant" (as described in the Introduction).

Results and discussion

Figure 7 shows the mean *actual matches* averaged across subjects for each wooden test plate and lamp. Also shown are the *matches of reflected light,* the *correct matches,* and the *best possible match based on estimating* colors *of lamps*. Color constancy is quite good: the *actual matches* lie very close to the *correct matches* (far from the *matches of reflected light*). This is not what one would predict from the poor estimates of the color of the illumination shown in Figure 4.

The average within subjects standard deviations for the matches, in terms of distance in CIE_{xy}, were 0.057 and 0.052 for the x and y coordinate, respectively. Thus, there was slightly less variability in color matches for the wooden test plates than there was for estimating the illuminants (although the difference between the mean coordinates makes this comparison questionable). The mean correlation between how well subjects performed on the two tasks was 0.02 with a standard deviation of 0.38 (across lamps).

Even the *best possible match based on estimating colors of lamps* cannot account for the *actual matches*: the systematic errors (relative to a *correct match*) cannot be accounted for by a single systematically misjudged color of the lamp. The CIE_{xy} coordinates for our fitted lamp are almost identical to the values set to match the similar lamp illuminating the scene (mean ± SD: 0.365 ± 0.037; 0.336 ± 0.037), but this cannot be considered as support for the Illuminant Estimation Hypothesis because it must be so if surface reflectance is judged more or less correctly

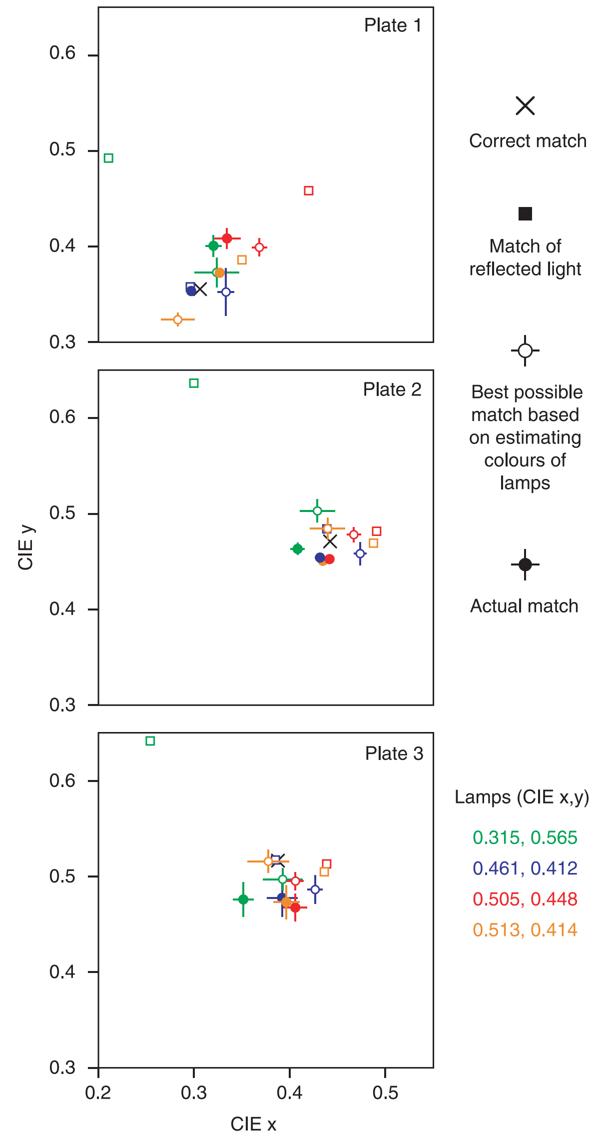

Figure 7. Estimates of surface reflectance. Matches for each of the three wooden test plates (panels) and four experimental illuminants (each represented by a different color). Closed disks: mean *actual matches* with standard errors across subjects' mean values. Squares: *matches of reflected light*. Crosses: *correct matches*. Open disks: *best possible match based on estimating colors of lamps,* with standard errors based on the variability between subjects.

(due to the way we fit the data). The systematic shifts in different directions between the open and solid symbols in Figure 7 show that the errors that our subjects made are not readily interpreted as misjudgments of the color of the light illuminating the color selector.

When we fit the data to obtain the *best possible match based on estimating colors of lamps,* we assumed that the spectral power distributions were well characterized by the three values that we used to characterize our stimuli. Although we also directly measured the coordinates of a correct match in order to circumvent this assumption, the veridical value that we obtain by doing so (or which one could obtain by measuring the full spectral distribution) does not really resolve the ambiguity because the visual system does not have access to the spectral power distributions underlying the cone responses, so it cannot be expected to detect deviations from the calculations given in Appendix A. To the extent that our subjects' color vision is represented accurately by the CIE color space and the standard cone functions used in Appendix A, we can predict what subjects would judge to be the same on the basis of those calculations (assuming that they correct fully for the difference between the lamps). Figure 8 shows that this does not give values that are closer to the actual matches than what we have called the correct match (the actual matches even appeared to be closer to the correct match, but a paired t-test shows that the difference is not significant).

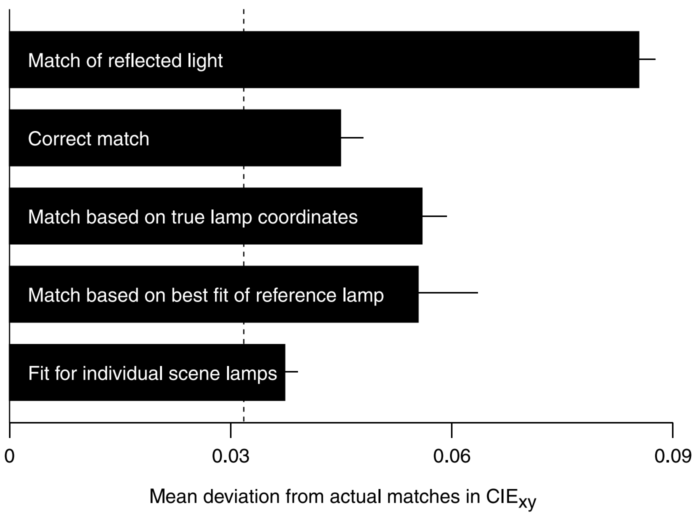

Figure 8. Average distance between the *actual matches* and various predictions for the matches. From top to bottom the predictions are: matching the light reaching the eye (*match of reflected light*; i.e., no color constancy), matching what the wooden test plate reflects when it is placed under the reference lamp (*correct match*; i.e., perfect color constancy), matching what one would expect the wooden test plate to reflect at the reference position given what it reflects within the scene and the measured CIE_{xy} values of the lamps (*match based on true lamp coordinates*; i.e., full von Kries scaling), matching what one would expect the wooden test plate to reflect at the reference position given what it reflects within the scene, the estimated chromaticity of the illumination of the scene, and the chromaticity of the reference lamp that provides the closest values to the actual matches (*match based on best fit of reference lamp*), and a similar prediction whereby the chromaticity of the hypothetical reference lamp was fit separately for each scene lamp (*fit for individual scene lamps*). The underlying calculations are explained in Appendix A. The dashed line shows the average distance between the predictions of perfect color constancy and full von Kries scaling. All values are based on individual subjects' data. Error bars indicate standard errors between subjects.

We interpret the difference between the two above-mentioned estimates of what constitutes perfect color constancy (dashed line in Figure 8) as a consequence of transforming spectral power distributions into three coordinates (CIE_{xyY} or the stimulation of three kinds of cones) and thereby as an illustration of why human color constancy cannot be perfect. However, the value that we report probably overestimates this problem a bit because measurement errors and effects of the precise viewing geometry under the reference lamp (which was not entirely fixed) also contribute to this difference. One reason to suspect that the dashed line overestimates the problem is that the actual settings were significantly closer to the *correct match* than to the *match based on the true lamp coordinates* ($t_6 = 5.55$; $p < 0.01$).

Despite the additional fit parameters, the match based on fitting the reference lamp was no better than either of the estimates based on full color constancy. It was significantly better than matching the reflected light ($t_6 = 4.05$; $p < 0.01$), as was already obvious from Figure 7. Fitting a separate reference lamp for each scene (which is equivalent to fitting the perceived chromaticity of the lamp illuminating each scene) did improve the match, indicating that if an illuminant is estimated it neither matches the estimated chromaticity (*match based on best fit of reference lamp*) nor the true chromaticity (*match based on the true lamp coordinates*).

Matches were made by selecting paper samples. There were obviously a limited number of such samples. That this did not limit subjects substantially is evident from the fact that each subject chose several samples as matches for each plate under each lamp. To nevertheless get some idea of the chromatic resolution within the relevant regions of color space, we determined the distance (in CIE_{xy}) to the nearest chosen sample from each sample that was ever chosen. The median of these values is 0.01. Since our analyses are based on average settings the relevant resolution is even better. From Figure 7, we can see that on average subjects are seldom off the correct match by more than a few steps of the pantone color selector.

General discussion

We can clearly reject the strong version of the Illuminant Estimation Hypothesis. Subjects are not good at estimating the illuminant's color whereas their surface color estimates are quite accurate. Moreover, there was no correlation between how well subjects could estimate the color of the lamp and how well they could estimate the color of the surface.

A weaker version of the Illuminant Estimation Hypothesis, whereby subjects' judgments are based on an estimate of the illuminant but the latter can be quite incorrect, is more difficult to reject. Any error in judging a surface's color can be interpreted as a misjudgment of the illumination. Thus, being able to describe the data in terms of an equivalent illuminant (Brainard et al., 1997; Speigle & Brainard, 1996) is not enough to conclude that such an illuminant is really estimated. Our reason for also considering the weaker version of the Illuminant Estimation Hypothesis to be unlikely is that even finding the hypothetical misjudgment of the illumination that best fits the data did not reproduce the observed errors particularly well in our study. This is critical if the Illuminant Estimation Hypothesis is to be considered as more than just an alternative way of describing the data, because the only advantage of interpreting judgment errors in terms of errors in judging the illumination is that the latter should hold for the whole scene. Of course, we changed the scene to some extent whenever we replaced a plate, so one could argue that subjects' estimates of the illumination need not be the same for all three plates. But why should the plate be critical for judging the chromaticity of the illumination when there were so many other objects in the scene (see Figure 6)? Thus, although our results cannot reject the weaker version of the Illuminant Estimation Hypothesis they suggest that there is no benefit in describing errors in perceived color in terms of misjudging the illumination rather than in terms of misjudging the reflectance (e.g., from a spatial comparison) or of misjudging the light reaching the eye (e.g., due to cone adaptation).

Our results complement recent results showing that improving information about the illuminant does not necessarily help to judge surface colors (Amano, Foster, & Nascimento, 2005, 2006). That subjects' estimates of the illuminant's color were so poor in the first part of our study is remarkable, because subjects could have used specular highlights that were abundant in our experimental scene. Highlight can give direct information about the chromaticity of the illuminant (D'Zmura & Lennie, 1986; Lee, 1986). However, the highlights in our experimental scene always looked "whitish" (desaturated), perhaps as a result of their high luminance (so that all three cone types are stimulated close to maximally). This nonlinearity may explain why subjects estimated the color of the illuminants to be more desaturated (although we presented an alternative explanation in the Introduction; a partial failure of color constancy).

Helmholtz (1867/1962) proposed that the illuminant component in the light reaching the eyes is judged by making unconscious inferences based on past experience. In our task, subjects had to judge the illuminant's color by making conscious, explicit estimates. Thus, it could be that the Illuminant Estimation Hypothesis holds at an unconscious level that is impenetrable to empirical study. We here show that if the visual system uses an estimate of the color of the illuminant in order to achieve color constancy, it does not use the color that is judged at a conscious level. If estimation of the illumination occurs at an unconscious level, the question is how detailed the analysis of the illumination is, because a very simple unconscious judgment, such as taking the average chromaticity of a scene as an indication of the illuminant's chromaticity, can just as well be described as relying on invariant properties of a scene to obtain color constancy.

Figure 9. Would you have thought that the sun is so orange (mirror reflection in tall building) if you had only seen the lower buildings? Does this influence how you see the white surfaces?

Conclusion

We show that judgments of surface color do not rely on explicitly estimating the color of the illumination. An illustration of this phenomenon is shown in Figure 9.

Appendix A

We used the principles outlined in Appendix C of Lucassen and Walraven (1993) to convert CIE$_{xyY}$ values into (relative) stimulation of l, m, and s cones and vice versa. These transformations are based on the Vos–Walraven cone spectral sensitivity functions. The x and y coordinates are adjusted to give x' and y'

$$x' = \frac{1.0271x - 0.00008y - 0.00009}{0.03845x + 0.01496y + 1}$$
$$y' = \frac{0.00376x + 1.0072y + 0.00764}{0.03845x + 0.01496y + 1}, \quad \text{(A1)}$$

which are used to calculate

$$X = (x'/y')Y$$
$$Z = ((1-x'-y')/y')Y, \tag{A2}$$

and finally cone stimulation values

$$l = 0.07778X + 0.27224Y - 0.01856Z$$
$$m = -0.15516X + 0.45692Y + 0.02969Z \tag{A3}$$
$$s = 0.33140Z.$$

These l, m, and s units are used in the color constancy computations, after which the outcome is transformed back into CIE_{xyY} values

$$X = 5.87451l - 3.50013m + 0.64254s$$
$$Y = 1.99485l + m + 0.02212s \tag{A4}$$
$$Z = 3.01752s,$$

then

$$x' = X/(X+Y+Z)$$
$$y' = Y/(X+Y+Z), \tag{A5}$$

and finally

$$x = \frac{1.00709x' + 0.00008y' + 0.00009}{-0.03867x' - 0.01537y' + 1.0345}$$
$$y = \frac{-0.00347x' + 1.02710y' - 0.00785}{-0.03867x' - 0.01537y' + 1.0345}. \tag{A6}$$

To predict subjects' matches in terms of estimates of illuminants, we consider the stimulation of each kind of cone by light reflected from the surface of interest (S_l, S_m, S_s) to be a product of the scene's illumination (expressed in terms of cone stimulation; I_l, I_m, I_s) and the plate's reflectance (expressed in terms of the percentage that is reflected for light stimulating each kind of cone; R_l, R_m, R_s), so

$$S_i = I_i R_i \qquad (\text{for } i = l, m, s). \tag{A7}$$

To the extent that they are good approximations (see below), these equations apply both to the wooden test plate within the scene and to the light from the selected sample of the color selector. The equivalent illumination hypothesis proposes that they also apply to perceived reflectance and illumination. Since the task was to match the two surfaces in terms of reflectance, we can assume that the perceived reflectance (and thus R_l, R_m, and R_s) is the same for the test plate and the matched sample. Since subjects gave us direct estimates of the perceived chromaticity of the illuminant (and thus of the relative values of I_l, I_m, and I_s) in the illuminant estimation experiment, and we measured the light reaching the eye from the test plates (S_l, S_m, and S_s), we can easily estimate the perceived reflectance ($R_i = S_i/I_i$). Since the perceived reflectance is the same for the matched sample, we can now fit values for the illumination (new values for I_i, representing the perceived chromaticity of the reference lamp) in order to try to reproduce the measured light reaching the eye from the matched sample. We consider the illumination that minimized the squared distances in CIE_{xy} between the calculated and measured values to be the best fit. The calculated values for this illumination are the "best possible match based on estimating colors of lamps."

Several issues about this procedure need to be clarified. The first is that we only determined the relative values of I_l, I_m, and I_s in the illuminant estimation experiment. Since the luminance is independent of the chromaticity in our equations (luminance is a linear scaling factor for the cone stimulation) and we only consider the perceived chromaticity (we minimize distances in CIE_{xy} ignoring CIE_Y) this is not a problem. The second issue is that in assuming that the reflectance for each kind of cone is the same for the two surfaces that are matched, we implicitly assume that reflectance in terms of cone stimulation is independent of the detailed spectral properties of the surface and of the spectral power distribution of the illumination. This is certainly not true (metamers under one illumination need not be metamers under different illumination; Brainard, 2003; Young, 1987) but is often a reasonable approximation (Nascimento, Ferreira, & Foster, 2002). We can evaluate how well this approximation holds for the lamps and plates used in our study by comparing the CIE_{xy} values of the light from the plates under the reference lamp, with what we would expect given the light from the plates within the scene and the measured chromaticity of the lamps. We will call this expected value the *match based on true lamp coordinates*. It is calculated in the manner described above, but using the measured values of I_i for the two lamps involved to predict values of S_i for the color selector given the measured values of S_i within the scene. This can be considered as a measure for the limitation of color constancy.

Appendix B

Subjects' average CIE_{xy} color matches for the illuminant estimation experiment (in the presence of objects with known colors).

Subject	Lamp 1	Lamp 2	Lamp 3	Lamp 4
1	(0.282, 0.368)	(0.350, 0.350)	(0.419, 0.414)	(0.389, 0.355)
2	(0.287, 0.437)	(0.307, 0.327)	(0.391, 0.406)	(0.355, 0.353)
3	(0.226, 0.313)	(0.382, 0.432)	(0.473, 0.400)	(0.543, 0.355)
4	(0.302, 0.466)	(0.307, 0.295)	(0.439, 0.417)	(0.465, 0.405)
5	(0.275, 0.349)	(0.306, 0.312)	(0.369, 0.373)	(0.363, 0.350)
6	(0.307, 0.502)	(0.324, 0.332)	(0.455, 0.412)	(0.420, 0.416)
7	(0.296, 0.513)	(0.325, 0.332)	(0.425, 0.433)	(0.460, 0.393)

Appendix C

Subjects' average CIE_{xy} color matches for the color constancy experiment.

Plate 1

Subject	Lamp 1	Lamp 2	Lamp 3	Lamp 4
1	(0.336, 0.379)	(0.295, 0.335)	(0.311, 0.382)	(0.339, 0.378)
2	(0.272, 0.367)	(0.306, 0.359)	(0.282, 0.403)	(0.307, 0.363)
3	(0.330, 0.392)	(0.306, 0.359)	(0.312, 0.375)	(0.318, 0.363)
4	(0.333, 0.416)	(0.285, 0.364)	(0.378, 0.434)	(0.328, 0.382)
5	(0.325, 0.448)	(0.306, 0.359)	(0.383, 0.453)	(0.338, 0.381)
6	(0.337, 0.387)	(0.293, 0.349)	(0.340, 0.398)	(0.337, 0.387)
7	(0.326, 0.423)	(0.306, 0.359)	(0.350, 0.420)	(0.336, 0.364)

Plate 2

Subject	Lamp 1	Lamp 2	Lamp 3	Lamp 4
1	(0.442, 0.452)	(0.443, 0.452)	(0.457, 0.447)	(0.456, 0.448)
2	(0.409, 0.452)	(0.414, 0.455)	(0.419, 0.460)	(0.438, 0.456)
3	(0.425, 0.461)	(0.446, 0.456)	(0.441, 0.454)	(0.437, 0.461)
4	(0.391, 0.496)	(0.431, 0.457)	(0.450, 0.455)	(0.424, 0.457)
5	(0.391, 0.457)	(0.448, 0.454)	(0.448, 0.454)	(0.441, 0.435)
6	(0.422, 0.459)	(0.417, 0.457)	(0.443, 0.455)	(0.433, 0.459)
7	(0.398, 0.474)	(0.441, 0.459)	(0.450, 0.455)	(0.432, 0.451)

Plate 3

Subject	Lamp 1	Lamp 2	Lamp 3	Lamp 4
1	(0.356, 0.433)	(0.414, 0.463)	(0.416, 0.466)	(0.418, 0.459)
2	(0.316, 0.558)	(0.410, 0.457)	(0.412, 0.466)	(0.414, 0.455)
3	(0.367, 0.471)	(0.411, 0.461)	(0.395, 0.429)	(0.401, 0.458)
4	(0.316, 0.528)	(0.302, 0.597)	(0.338, 0.550)	(0.316, 0.582)
5	(0.381, 0.457)	(0.381, 0.457)	(0.422, 0.456)	(0.402, 0.463)
6	(0.385, 0.433)	(0.416, 0.460)	(0.430, 0.455)	(0.417, 0.457)
7	(0.342, 0.464)	(0.412, 0.463)	(0.428, 0.464)	(0.408, 0.453)

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